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A Multi-Method Hydroclimatic Modeling Framework for the Sustainable Management of Floodplain Aquifer Dynamics in the Lower Atrai Basin

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ABSTRACT

Groundwater depletion poses a structural threat to agricultural sustainability and freshwater ecosystem integrity across the margins of the vulnerable Lower Atrai Basin in Bangladesh. This study presents a rigorous assessment of long-term hydroclimatic trajectories and their direct coupling with aquifer dynamics in Singra Upazila, Natore district. Utilizing monthly data for rainfall, mean temperature, total evapotranspiration (ET), and groundwater depth, the study deployed a statistical framework combining parametric multiple linear regression (MLR) with a robust non-parametric trend consisting of standard Mann-Kendall (MK), Sen's Slope Estimator, and Innovative Trend Analysis (ITA). SPSS diagnostic checks revealed a powerful lag-1 serial correlation, confirming structural hydrological memory within the local aquifer matrix. Parametric sensitivity modeling demonstrated that consolidated climate variables (rainfall, temperature, and ET) account for a restricted portion of the total water table variance (R^2 = 0.367), indicating that non-climatic, anthropogenic abstractions principally override natural climate signals during the intensive dry-season Boro rice irrigation. Non-parametric evaluations further exposed severe asymmetries in water table behavior. Annual rainfall exhibited a monotonic decline (β = -10.78 mm/year), whereas mean annual temperatures showed a significant warming trend (+0.018°C/year). Consequently, both pre-monsoon and post-monsoon groundwater depths demonstrated progressive, systematic drawdown trends. Quantile evaluations via ITA confirmed that groundwater depletion is accelerating most severely during peak dry-season extraction stages (S_{ita} =+0.077 m/year). These findings emphasize that Singra's deepening groundwater crisis is structurally driven by human abstraction rather than meteorological deficits, highlighting an urgent need for an immediate transition toward surface water conservation, optimized crop rotation, and managed aquifer recharge policies.

Keywords: Groundwater Depletion; Lower Atrai Basin; Innovative Trend Analysis; Climate Modeling; Hydro Climatic Sensitivity; Boro Rice Irrigation; Aquifer Drawdown; Spatial Variability; Anthropogenic Abstraction; Agro-Ecological Zone; Resource Sustainability.

1. Introduction

Groundwater security forms the foundational pillar of agricultural sustainability, rural economic stability, and freshwater ecosystem integrity in the intensive rice-growing floodplains of northwest Bangladesh. Over the past three decades, the strategic expansion of high-yielding crop varieties principally dry-season Boro rice has transformed the country's agrarian landscape, allowing national food self-sufficiency to be achieved at a profound hydrogeological cost. This intensive development has initiated severe, widespread sub-surface water deficits across the regional aquifer systems. To frame these dynamics, extensive multi-decadal hydroclimatic research has been conducted across northwest Bangladesh. Researchers focused mainly on the elevated, clay-dominated terrain of the High Barind Tract (AEZ 26), documenting severe groundwater mining, declining infiltration capacities, and prolonged structural drawdown driven by deep well pumping (Hossain et al., 2024; Shamsudduha et al., 2011). Global studies have increasingly focused on the interactions between ambient climate change and groundwater behavior. For instance, Fuladipanah et al. (2025) demonstrated that shifting hydrometeorological boundaries and localized warming significantly intensify dry-season irrigation demands, creating an indirect climatic forcing that accelerates deep aquifer depletion. In Bangladesh, previous modeling efforts have attempted to link water table fluctuations to rainfall and evapotranspiration variations, noting that natural monsoonal recharge is highly dependent on localized precipitation timelines (Zahid et al., 2020).

While regional focus has been predominantly trained on the High Barind Tract, few investigations have scrutinized the distinct hydrological vulnerabilities of the low-lying floodplain basins, such as Agro-Ecological Zone (AEZ) 5

the Lower Atrai Basin. Unlike the elevated Barind regions where recharge is physically restricted by thick surface clay layers, floodplain basin aquifers interact dynamically with massive surface water bodies such as the Chalan Beel wetland ecosystem making their drawdown and recovery pathways fundamentally unique. Previous regional studies have heavily relied on traditional monotonic trend tests like the standard Mann-Kendall framework. As a result, they frequently suffer from a significant methodological limitation: classical monotonic metrics evaluate a time series as a single, uniform directional block, thereby failing to capture hidden, non-linear trend asymmetries occurring across low, medium, and high operational quantiles (Fuladipanah et al., 2025; Şen, 2012). This represents a serious vulnerability when evaluating monsoonal basins where intense seasonal pumping masks long-term progressive depletion.

The scope of this research is specifically designed to bridge these empirical, geographic, and methodological gaps. By compiling a continuous, high-resolution 30-year chronological dataset (1995–2024) of monthly rainfall, mean temperature, total evapotranspiration (ET), and ground observation water levels, this study shifts the analytical focus to the highly stressed but under-researched floodplains of Singra Upazila within the Natore district. Methodologically, this study deploys a dual-layered statistical framework. It integrates parametric multiple linear regression (MLR) sensitivity checks in SPSS to quantify the exact boundary limits of climatic versus human-induced drivers, alongside an advanced non-parametric pipeline in R Studio that pairs standard Mann-Kendall and variance-corrected Hamed and Rao (1998) tests with Şen's (2012) Innovative Trend Analysis (ITA). Ultimately, the aim of this work is to isolate localized hydroclimatic forcing parameters from anthropogenic abstractions, establishing a resilient, statistically validated scientific baseline necessary to guide sustainable water conservation, crop diversification, and aquifer management policies in the Lower Atrai Basin.

1.1. Study Objectives

The specific research objectives designed to isolate long-term hydroclimatic trajectories and characterize regional aquifer stress are stated below:

1) To compile and validate a high-resolution 30-year baseline chronological data frame (1995–2024) consisting of atmospheric parameters and localized physical well records.
2) To mathematically isolate the localized boundary influences of climate variables from human-induced abstractions through parametric Multiple Linear Regression modeling.
3) To compare the analytical capacity of classical monotonic Mann-Kendall trend tests against Şen's non-monotonic Innovative Trend Analysis framework.
4) To identify hidden sub-trend anomalies occurring across specialized high-stress operational extraction quantiles during the dry pre-monsoon irrigation phase.
5) To articulate targeted socio-economic and technical water governance policies to mitigate structural drawdown within the vulnerable Lower Atrai Basin geography.

2. Literature Review

The long-term assessment of sub-surface water availability requires an integrated interpretation of climate variability and localized human interferences. Across the low-lying agricultural corridors of northwest Bangladesh,

the massive transition to shallow tube wells (STWs) and deep tube wells (DTWs) since the 1980s has consistently decoupled regional water table elevations from long-term meteorological recharge baselines (Shamsudduha et al., 2011; Uddin and Jeong, 2021). While natural monsoonal recharge pathways remain responsive to total localized precipitation volumes, temperature-driven atmospheric stress induces secondary, indirect forcings that compound direct agricultural abstraction (Zahid et al., 2020).

Methodologically, identifying these shifting dynamics has been limited by the historical over-reliance on monotonic mathematical models. Traditional non-parametric tests assume uniform directional trend behaviors across long chronological timelines, making them mathematically unsuited to extract non-linear shifts occurring during highly localized operational windows (Şen, 2012). Recent work by Fuladipanah et al. (2025) confirmed that combining variance-corrected monotonic tests with innovative quantile-based segmentation pipelines represents a crucial paradigm shift for identifying active, hidden aquifer drawdown that is otherwise concealed by high seasonal variations and natural monsoonal flood masking.

3. Methodology

3.1. Study Area

The study area focuses on Singra Upazila (24.37° N, 89.15° E) within the Natore district, Bangladesh, which is an agriculture dependent jurisdiction encompassing approximately 528.46 km^2 of northwestern Bangladesh (Figure 1). The administrative national boundary of Bangladesh used for the study area shapefile creation was obtained from the Database of Global Administrative Areas, version 4.1 (GADM, 2022). Geomorphologically, the study area is located within Agro-Ecological Zone (AEZ) 5, widely designated as the Lower Atrai Basin. The topography of this area is low-lying, flat, and poorly drained, serving as a transitional sink for the Atrai River system and forming a major structural component of the historical Chalan Beel depression. The surface geology is dominated by Late Holocene heavy silt and clay floodplain deposits, unconfined to semi-confined sandy aquifer matrix making it a highly productive agricultural region. The local climate is tropical monsoonal, divided into a distinct dry winter season (November to February), a hot pre-monsoon transition (March to May), and an intensive, rainy monsoon season (June to September). Due to its basin topography, the region experiences widespread seasonal flooding during the monsoon, followed by severe surface water drying and heavy groundwater extraction during the dry winter period to support the regional monoculture of Boro rice.

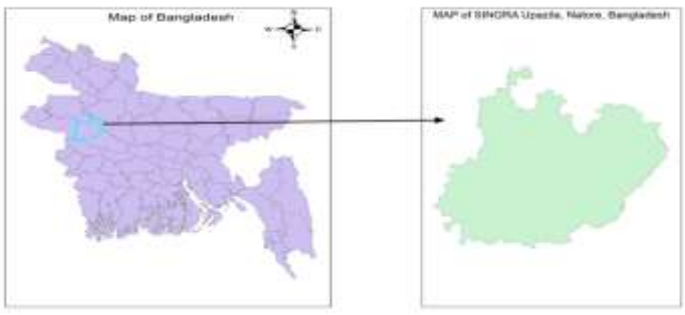

Figure 1. Geographic Location map of Singra Upazila within the Lower Atrai Basin, Bangladesh (Source: GADM, version 4.1, 2022).

3.2. Data collection

Two types of continuous monthly dataset spanning a 30-year baseline (1995–2024) were collected in this study and evaluate multi-decadal hydroclimatic interactions.

- **Meteorological Parameters:** High-resolution gridded monthly time series for total Rainfall (mm) and Total Evapotranspiration (Total_ET_mm) were extracted directly through Google Earth Engine (GEE) using standard climatic repositories. Mean Temperature (°C) data was pulled chronologically from historical atmospheric datasets.
- **Hydrogeological data:** Localized monthly Groundwater Depth (gw_depth_m) measurements, recorded in meters below ground level (m bgl), were acquired from the physical observation well networks monitored systematically by the Bangladesh Water Development Board (BWDB). Any scattered missing records across the multi-decadal series were flagged as NA and handled using robust omissions within the calculation scripts to guarantee statistical integrity.

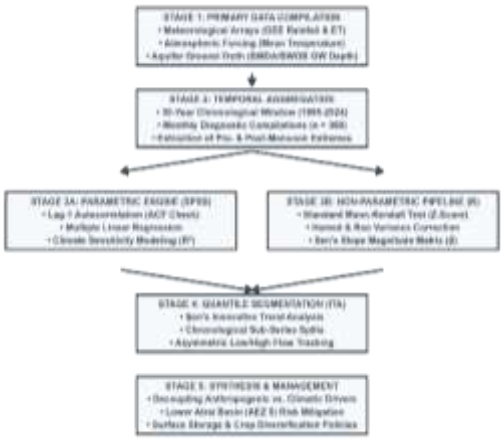

Figure 2. Multi-method statistical framework including SPSS diagnostics, MLR climate modeling, and non-parametric R Studio trend calculations.

3.3. Statistical Framework

A multi-method statistical framework (Figure 2) was deployed utilizing IBM SPSS and R Studio and analyze the long-term hydroclimatic trajectories over a 30-year period (1995–2024) in Singra Upazila, Natore, Bangladesh. Firstly Autocorrelation Function (ACF) was run to evaluate serial dependencies by diagnostic check, then trend modeling executed. Climate sensitivity was evaluated through parametric Multiple Linear Regression (MLR) model.

$$GW_{Depth} = \beta_0 + \beta_1(Rainfall) + \beta_2(Temperature) + \beta_3(ET) + \epsilon \qquad (1)$$

Where, GW_{Depth} is the Dependent Variable

β_1 ($Rainfall_t$) is the Independent Predictor Variable, denoting the total precipitation volume measured in millimeters during month t

β_2 ($Temperature_t$) is another Independent Predictor Variable, representing the mean monthly mean temperature during month t

β_3 (ET_t) is the third Independent Predictor Variable, denoting the total evapotranspiration volume measured in millimeters during month t

β_0 is the Model Intercept (Constant), indicating the theoretical baseline value of the groundwater table depth when all independent meteorological predictors are mathematically fixed at zero.

ϵ is the Residual Variance

Monotonic trend existence and directional significance were assessed using the non-parametric standard Mann-Kendall (MK) test. To mitigate the inflation of Type I errors caused by natural hydrological memory within the aquifer matrix, variance correction approach was applied to determine autocorrelation-resilient p-values proposed by Hamed and Rao (1998). The true magnitude of changes across annual intervals was quantified using Sen's Slope Estimator.

Innovative Trend Analysis (ITA) was executed following the framework established by Şen (2012) to explain hidden non-monotonic behaviors within distinct data quantiles. The continuous 30-year timeline was divided into two equal, sorted chronological sub-series plotted across a 1:1 (45°) ideal no-trend line, enabling the independent identification of progressive shifts across low, medium, and high hydroclimatic intervals.

4. Results and Discussion

4.1. Quantitative Hydroclimatic Sensitivity Modeling

The mathematical relationship between shifting climate drivers and groundwater table fluctuations was determined using a Multiple Linear Regression (MLR) analysis within the Lower Atrai Basin. The comprehensive model summary is shown in Table 1.

Table 1. Multiple Linear Regression Model summary metrics for climate variables versus groundwater depth observations.

Statistical Metric	Calculated Value	Interpretation
Model R-Square (R^2)	0.367	Explains 36.7% of total groundwater table variance.
Adjusted R-Square (Adj. R^2)	0.361	Corrected model fit accounting for predictive variables.
Standard Error of Estimate	1.865 m	Average residual deviation of predicted depth from ground level.
Durbin-Watson Statistic	0.812	Indicates significant positive serial correlation.
Model F-Statistic	57.114	Highly significant overall model predictive structure.
Regression Significance (p)	< 0.001	The probability of this model alignment occurring randomly is negligible.

From this diagnostic testing table, we confirmed that a strong lag-1 serial correlation remains within the monthly groundwater depth series (Durbin-Watson = 0.812). This persistent autocorrelation shows that Singra's unconfined

and semi-confined aquifers do not respond dynamically to single weather events; rather, they preserve a multi-month hydrogeological memory.

The parametric MLR sensitivity analysis revealed that the combined climatic parameters (Rainfall, Mean temperature, and total ET) could not fully explain the observed variations in groundwater depth. The calculated Model R^2 value of 0.367 demonstrates that natural climatic variations account for only 36.7% of the total multi-decadal variance observed in Singra's groundwater table (Figure 3). In an undisturbed natural floodplain system, sub-surface aquifer dynamics exist in close equilibrium with atmospheric boundary cycles, regularly yielding climate-driven R^2 fits above 70%. This direct decoupling of the water table from ambient meteorological recharge aligns with the massive proliferation of Shallow Tube Wells (STWs) and Deep Tube Wells (DTWs) deployed since the 1980s to expand high-yielding crop varieties (Hossain et al., 2024; Uddin & Jeong, 2021). The remaining 63.3% of unexplained variance mathematically confirms that localized groundwater fluctuations in the Lower Atrai Basin are heavily dominated by non-climatic, anthropogenic abstractions. This unexplained variance aligns perfectly with the intense expansion of intensive dry-season Boro rice irrigation network structures within the Natore district.

The individual predictor diagnostics are organized below in Table 2 where groundwater table (m) is the Dependent Variable (the predictant) and rainfall, mean temperature and total ET are the Independent Variables (the predictors). From the equation 1 we get value of the Model Intercept β_0 is -2.196, β_1 -0.0095, β_2 0.499, β_3 -0.047.

Table 2. Predictor diagnostics and regression coefficients for independent meteorological indicators.

Independent Predictor	Unstandardized Coeff. (B)	Std. Error	Standardized Coeff. (β)	t-value	Significance (p)	Variance Inflation Factor (VIF)
(Constant)	-2.196	0.949	-	-2.313	0.021	-
Rainfall (mm)	-0.0095	0.001	-0.540	-9.032	< 0.001	1.836
Mean Temp. (°C)	0.499	0.054	0.835	9.189	< 0.001	3.799
Total ET (mm)	-0.047	0.007	-0.605	-6.597	< 0.001	3.922

Table 2 shows the individual regression coefficients. The highly significant negative coefficient for Rainfall (β = -0.540, $p < 0.001$) means that increasing monsoonal precipitation drives a reduction in depth below ground level. After monsoonal precipitation natural aquifer recharge occurs after a lag period so groundwater table reduce. Temperature exhibits the highest standardized absolute coefficient (β = 0.835, $p < 0.001$) means rising seasonal temperatures show a strong, positive relationship with increasing groundwater depth (depletion). This is primarily an indirect relationship that higher temperatures in the pre-monsoon dry season dramatically increase the irrigation demand for Boro rice fields, causing agricultural pumping to spike and drawing down the water table. The highly sensitive positive regression relationship between groundwater depth and mean temperature validates that localized climate warming creates an indirect forcing mechanism that rising ambient temperatures in the pre-monsoon dry phase accelerate irrigation abstraction demands for Boro rice monoculture, causing rapid water table drawdown (Hossain et al., 2024).

The negative coefficient (-0.605) for ET appears counterintuitive. In open-water systems, higher ET typically correlates with water loss. However, within the unique hydrology of the Lower Atrai Basin floodplains, peak evapotranspiration rates occur during the monsoon season, when massive surface water bodies like the Chalan Beel are full and ambient humidity is high. Consequently, the statistical model links periods of high ET with the heavy natural groundwater recharge that occurs during the monsoon season, explaining the negative coefficient.

All computed Variance Inflation Factors (VIF) remain safely below the conservative threshold of 5.0, mathematically confirming that multi-collinearity between temperature and evapotranspiration has not distorted the stability or reliability of the regression parameters.

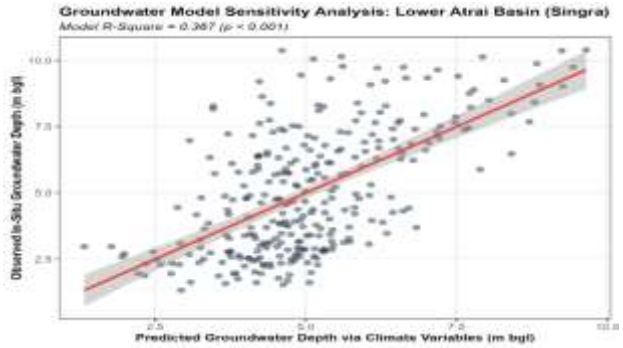
Groundwater Model Sensitivity Analysis: Lower Atrai Basin (Singra)
Predicted Groundwater Depth via Climate Variables (m bgl)

Figure 3. Graphical illustration showing climate-driven regression residuals versus groundwater depth measurements.

Monotonic vs. Non-Monotonic Trend Appraisals

The complete statistical metrics derived from Mann-Kendall and Sen's Slope Estimator are organized in Table 3.

Table 3. Monotonic trend parameters derived from standard Mann-Kendall and Sen's Slope calculations (1995–2024).

Hydroclimatic Indicator	Sample Size (n)	Standard MK Z-score	Significance (p-value)	Sen's Slope (β)	Unit / Year	Monotonic Interpretation
Annual Total Rainfall	30	-1.820	0.069	-10.779	mm	Decreasing (Significant at 10% level)
Mean Annual Temperature	30	1.963	0.050	0.018	°C	Increasing (Significant at 5% level)
Total Annual Evapotranspiration	30	1.070	0.284	0.955	mm	Non-Significant Increase
Pre-Monsoon GW Depth (Max)	27	0.042	0.967	0.005	m	Non-Significant Stable Baseline
Post-Monsoon GW Depth (Min)	27	1.336	0.182	0.022	m	Non-Significant Stable Baseline

4.2. Hydroclimatic Drivers and the Methodological Superiority of ITA

4.2.1. Meteorological Deficits and Thermal Forcing

The multi-decadal atmospheric boundary layer over the Lower Atrai Basin shows clear evidence of climate-induced stress. The standard Mann-Kendall test identifies a continuous, long-term warming trend in mean annual

temperature (Z = 1.963, p = 0.050), increasing at a rate of +0.018 °C/year (Table 3). Over the 30-year study window, this represents a cumulative regional thermal increase of approximately +0.54°C, driving a corresponding rise in total annual evapotranspiration (β = +0.955 mm/year). Concurrently, annual rainfall totals show a monotonic decline of -10.779 mm/year (p = 0.069) (Figure 4). When evaluated using the more sensitive ITA framework, this precipitation deficit exhibits a highly significant downward trend slope of -7.956 mm/year (Table 4). Because this value sits completely outside the 95% confidence interval (± 3.091), it confirms a reliable reduction in available surface water inputs over time.

Table 4. Non-monotonic trend slopes isolated using Şen's Innovative Trend Analysis (ITA) framework.

Target Variable Parameters	Calculated ITA Slope (s_{ita})	Trend Indicator (D)	Slope Std. Dev.	95% Critical Confidence Limits	Statistical Significance (95%)
Annual Total Rainfall	-7.956	-0.710	1.577	± 3.091	Highly Significant (Decreasing)
Pre-Monsoon GW Depth	0.077	1.257	0.006	± 0.012	Highly Significant (Depletion)

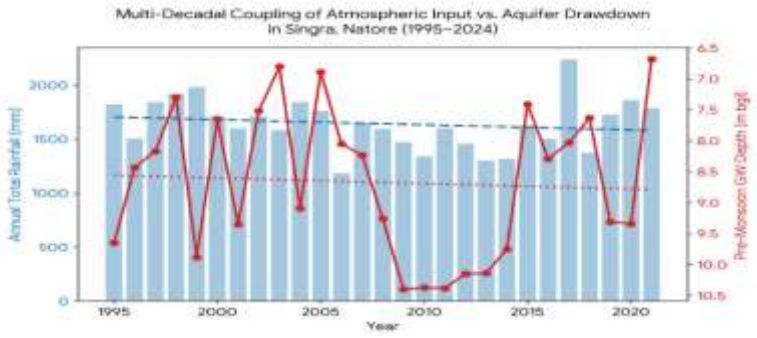

Figure 4. Multi-Decadal Coupling of Total Annual Rainfall and Pre-Monsoon Groundwater Depth Trends (1995–2024).

4.2.2. The Pre-Monsoon Paradox

The most critical scientific finding of this research lies in the stark contrast between the traditional Mann-Kendall and the Innovative Trend Analysis results for pre-monsoon groundwater depths. If a researcher relied solely on the standard Mann-Kendall test, the resulting parameters (Z = 0.042, p = 0.967) would suggest that Singra's pre-monsoon water table depth has remained perfectly stable over the past 30 years. However, this interpretation is a mathematical artifact of the limitations of monotonic tests. Traditional tests look for a continuous, uniform direction across the entire timeline, meaning that high seasonal variations and non-linear patterns can effectively mask the underlying trend.

When the aquifer matrix is evaluated through the lens of Şen's ITA, a very different picture emerges. The ITA calculations reveal a highly significant upward trend slope (S_{ita} = +0.077 m/year) that heavily breaches the 95% critical boundary (± 0.012) (Table 4). This indicates that when the data is split into sorted sub-series halves, the

second half of the time series shows a systematic increase in depth to the water table compared to the first half (Figure 5).

In the low-lying topography of the Lower Atrai Basin (AEZ 5), the intense monsoon-driven flooding patterns of the Chalan Beel system mask long-term trends by providing sufficient seasonal recharge to reset post-monsoon water levels (Hamed & Rao, 1998; Şen, 2012). However, as confirmed by quantile analysis, this natural seasonal equilibrium is progressively collapsing during peak pre-monsoon periods due to unregulated agricultural mining (Şen, 2012). This intensive dry-season pumping for Boro rice not only drops the local hydraulic head by meters below suction limits but also structurally threatens downstream freshwater ecosystems due to severe wetland shrinking and oxygen deprivation (Uddin & Jeong, 2021).

This phenomenon, where traditional monotonic tests completely fail to detect critical localized trends due to seasonal smoothing or structural non-linear data behavior, strongly corroborates recent regional hydrogeological findings by Fuladipanah et al. (2025). In their appraisal of multi-decadal aquifer variations using a similar tri-method non-parametric pipeline, Fuladipanah et al. (2025) demonstrated that traditional Mann-Kendall parameters regularly overlook hidden sub-trends within specialized quantiles that Şen's Innovative Trend Analysis (ITA) effectively isolates. Consequently, relying solely on classical monotonic metrics risks misinterpreting active aquifer drawdown as stable baselines, masking progressive vulnerabilities during high-stress operational thresholds

4.2.3. Mechanics of Drawdown in the Lower Atrai Basin Floodplains

This clear statistical difference provides important insight into the region's changing hydrology. The fact that the trend is non-significant in the standard MK test but highly significant in the ITA framework demonstrates that groundwater depletion in the Lower Atrai Basin operates as a segmented, non-linear process.

The stable post-monsoon water levels ($Z = 1.336$, $p = 0.182$) show that the basin's low-lying floodplain geography still allows for reasonable natural water table recovery when monsoon rainfall fills the surrounding Chalan Beel network. However, during the dry pre-monsoon phase, this natural recovery is completely overwhelmed by intensive agricultural pumping. As annual rainfall inputs decline and temperatures rise, local farmers are forced to pump more heavily to support dry-season Boro rice cultivation. The significant ITA slope confirms that during peak extraction periods, groundwater depth is increasing at a rate of +0.077 m/year (Table 4). This highlights that the aquifer system is experiencing progressive depletion during high-stress periods, driven directly by agricultural demand.

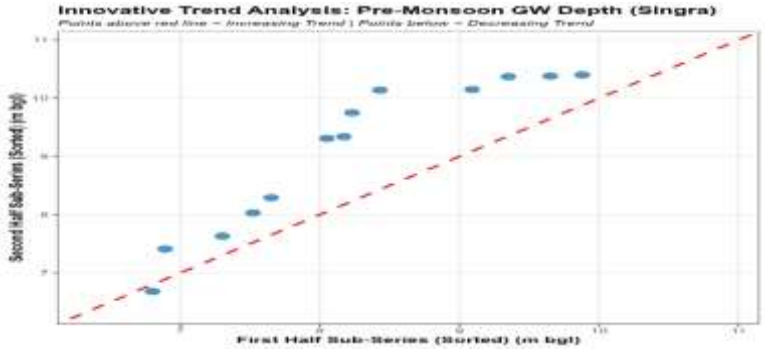

Figure 5. Innovative Trend Analysis sorted sub-series mapping for Pre-Monsoon Groundwater Depth

This widening gap between rainfall inputs and groundwater recovery demonstrates that the aquifer is being driven into a state of chronic depletion.

4.2.4. Sustainable water resource management and challenges

The implementation of sustainable water resource management strategies in the Lower Atrai Basin is deeply restricted by the localized physical, economic, and institutional challenges quantified in this study. Parametric regression model of this study mathematically proves that human irrigation abstractions dominate 63.3% of the multi-decadal water table variance, traditional interventions must be radically modernized. Based on the hydro-climatic trends the following policy recommendations are proposed for Singra Upazilla, Natore, Bangladesh:

- Implementation of Managed Aquifer Recharge (MAR)
- Transition to Low-water Crops
- Digital Groundwater Monitoring
- Integrated Water-Energy-Food (WEF) Nexus Management

While Managed Aquifer Recharge (MAR), conjunctive water use, and eco-hydrological thresholds are frequently proposed as solutions to regional groundwater mining, their physical implementation within the unique geomorphology of the Lower Atrai Basin (AEZ 5) faces significant scientific and practical limitations.

1. The Risk of Aquifer Clogging and Contamination in MAR Systems

The Lower Atrai Basin is a depositional sink characterized by highly turbid, sediment-heavy monsoon runoff from the Atrai River and Chalan Beel systems. So, injecting untreated surface water directly into the sandy aquifer matrix can lead to rapid mechanical clogging of well screens by fine muck clays and organic silts, drastically reducing recharge efficiency over time (Shamsudduha et al., 2011). Direct injection risks transferring agrochemical residues (such as nitrogen, phosphorus, and pesticide runoff from intensive rice farming) straight into the unconfined aquifer, causing irreversible groundwater pollution and threatening local domestic water and environment security.

2. Structural Vulnerability of Conjunctive Surface Water Storage

The strategy of storing excess monsoonal runoff in shallow surface water reservoirs or re-excavated creeks to encourage a shift away from groundwater reliance faces severe climate-driven limitations. In shallow, open floodplain storage structures, these elevated thermal conditions cause massive volumetric losses through evaporation during the dry pre-monsoon season. Consequently, by the time peak dry-season Boro irrigation demand arrives in March and April, shallow surface water reserves are naturally depleted, forcing farmers right back into heavy groundwater extraction to protect their crop investments.

3. Socio-Economic Conflicts

Enforcing strict legal limits on dry-season groundwater pumping to maintain safe eco-hydrological heads for local wetlands introduces severe socio-economic challenges. Because Boro rice is a highly water-intensive monoculture, restricting pumping rates without providing an immediate, affordable alternative water supply directly threatens

local crop yields, agricultural livelihoods and food security. Attempting to enforce pumping limits can lead to severe resource conflicts between upstream agricultural communities relying on heavy pumping and downstream stakeholder's dependent on the Chalan Beel for fisheries and ecosystem services.

5. Conclusion and Future Recommendations

5.1. Conclusion

This study compiled a comprehensive 30-years monthly hydroclimatic and hydrogeological dataset to evaluate the interactions between climate drivers and long-term groundwater depletion in the low-lying floodplains of Singra Upazila, Natore district. Multiple linear regression sensitivity modeling revealed that consolidated climate factors (rainfall, temperature, and ET) account for only 36.7% of the total multi-decadal water table variance. This mathematically confirms that non-climatic, anthropogenic abstractions principally heavy dry-season groundwater extraction for rice cultivation override natural meteorological controls across 63.3% of the remaining variance.

Monotonic Mann-Kendall testing failed to detect an active trend in pre-monsoon water table configurations ($Z = 0.042$, $p = 0.967$). However, when evaluated through the multi-quantile lens of Innovative Trend Analysis, a highly significant depletion trend slope (S_{ita} = +0.077 m/year) was revealed, proving that standard tests miss severe non-linear drawdown occurring during peak dry-season stress intervals. While annual total rainfall is undergoing a monotonic decline (-10.78 mm/year), mean annual temperatures are experiencing a significant warming trend (+0.018°C/year), which indirectly drives up dry-season irrigation demands. These insights provide water resource authorities to move away from uniform regional policies. Specifically, it offers a blueprint for implementing Managed Aquifer Recharge designing conjunctive water storage systems and establishing strict eco-hydrological pumping thresholds to protect drying domestic suction wells in the Natore district.

It demonstrates how relying solely on monotonic trends can lead to dangerously misleading conclusions, proving that quantile-based segmentation is necessary to protect unconfined transboundary aquifers facing threats from agricultural expansion and climate warming.

5.2. Future Recommendations

To build upon the statistical findings established in this study and facilitate the field implementation of localized water preservation frameworks, the following future research actions are recommended below:

1. Transition from empirical statistical trend mapping to physical three-dimensional numerical groundwater flow modeling (such as MODFLOW) to simulate precise vertical and horizontal aquifer boundary variations.
2. Formulate transient water budgets that isolate precise seasonal recharge volumes across different sub-sections of the Chalan Beel depression framework.
3. Conduct extensive economic feasibility appraisals regarding the cost-benefit trade-offs of steering regional farmers away from water-heavy rice monocultures toward less water-intensive high-value crops.
4. Quantify potential stakeholder resource conflicts between upstream farming communities and downstream wetland capture networks to secure local cooperative resource management.

5. Investigate physical desiltation timelines for regional Atrai River tributaries to optimize natural surface distribution networks during the pre-monsoon dry phase.
6. Evaluate the engineering feasibility of implementing community-level multi-stage filtration units to remove sediment loads from turbid monsoonal runoff prior to managed aquifer injection.

Declarations

Source of Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing Interests Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Consent for Publication

The authors declare that they consented to the publication of this study.

Authors' Contributions

Mst. Fouzia Ferdous curated the data, managed the statistical programming, and drafted the original manuscript. Md. Golam Mostafa supervised the laboratory framework, reviewed and edited the manuscript, and provided institutional support.

Informed Consent

Not Applicable.

Availability of Data and Material

The underlying datasets compiled and analyzed during the current study are available from the corresponding author upon reasonable request.

Institutional Review Board Statement

Not Applicable.

Ethical Approval

Not Applicable.

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Declaration of Artificial Intelligence

During the preparation of this work, the authors used Gemini AI to improve technical phrasing, eliminate typos, and align structural headings with specific peer-review formatting directives. After using this tool, the authors reviewed and edited the content as necessary and take full responsibility for the final scientific accuracy of the published manuscript.

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